# Wave-Induced Hydrodynamic Motion of Floating Structure with Prismoidal Shape

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***Abstract***

As developing ocean space and natural resources is increased, floating structure is gathering more interest. This paper is for experimental studies on pontoon-type floating structures to investigate the wave-induced hydrodynamic motion. A series of small-scale tests with various wave cases were performed on the pontoon models. A total of four small-scale pontoon models with different lateral shapes and bottom details were fabricated and tested under the five different wave cases. Six hydraulic pressure gauges and three accelerometers were attached on the bottom and top surfaces of the pontoon models and the wave-induced hydraulic pressure and acceleration by motion were measured during the tests. Finally, hydraulic pressures subjected to the bottoms of the pontoon models and the differences of acceleration by shape were compared with each other. As the results of this study, it was found that the wave-induced hydraulic pressures at the bottom and accelerations were dependent on the wave period as well as the wave height. The hydraulic pressures linearly increased according to the wave height and period. However, in the case of long wave periods, the wave-induced hydraulic pressure no longer increased. It was found that the shape of lateral cross-section and air gap affected the acceleration by motion. The prismoidal shape decreased the acceleration over 30 % compared to the box shape. Also, it was found that whereas the waffled bottom shape hardly influenced the wave-induced hydraulic pressure and acceleration, the prismoidal lateral shape significantly influenced the wave-induced hydraulic pressure subjected on the bottoms and acceleration of floating structures. Consequently the air gap effects of the prismoid shape contribute to decreasing the wave-induced hydraulic motion due to absorption of wave impact energy.

***Keywords***

*Pontoon; Prismoid Shape; Hydraulic Pressure; Acceleration*

## Introduction

After the first step toward sea with creation of a ship, mankind has been paying insatiable effort to develop vast ocean. With those efforts, nowadays the size and usage of marine structures are beyond our imagination. Huge cruise ships, containers or oil carriers, FPSOs (Floating Production and Storage Offloading) are the clear examples. Recent floating structures different from a ship shape for transportation, having a marine ground concept for creating marine space are gathering interest like floating harbor, floating airport, and drilling rigs. On these structures, men can work at sea feeling like doing that at land (Fig. 1).

In civil engineering field, even though two-third of this planet is cover with water, it has been true that most structures were built on the earth. One of the reasons is that structures basically require firm foundation. Of course there are so many structures built on the sea bed but it has some limitation to the various application of sea. Due to the recent issues of green energy, shortage of land by NIMBY, safe oil storage sites, the ocean is under development for expanding the territory and those make the civil engineers have much interest in floating structures.

Large floating offshore structures such as LNG terminals, storage vessels, and container terminals are exposed to severe offshore environment conditions such as waves, water pressure, and impact loads. Therefore, these floating offshore structures must satisfy particular design requirements. Floating structural systems should withstand the severe offshore environment and not allow permanent structural damage during service life. Also, structural members should absorb external impacts and deformation energy to prevent structural collapses [1, 2]. To satisfy these design requirements, floating offshore structures are constructed for high structural performance in bending and shear to support wave-induced bending moment and impact loads.

In order to reduce total weight and height of floating structures, it is important to reduce the hydraulic pressure subjected to bottom of floating structures and

limit acceleration within a certain range to make men's ordinary work possible[3, 4]. In this study, experimental studies were conducted on pontoon-type floating structures in order to investigate wave-induced hydrodynamic motion. A series of small-scale tests with various wave cases were performed on the pontoon models and the wave-induced hydraulic pressure on the bottom and acceleration on the top of pontoon models were measured. Finally, the hydraulic pressures subjected to the bottom and acceleration of pontoon models were compared each other.

(a) FLOATING HARBOR (MONACO)

(b) FLOATING AIRPORT (JAPAN)

FIG. 1 EXAMPLE OF AN IMAGE WITH ACCEPTABLE RESOLUTION

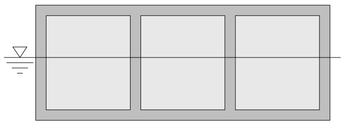
## Types of Floating Structures

Floating structures suitable to secure wide space for men to work as like on the earth are grouped into two categories; pontoon type and submersible type, as shown in Fig. 2.

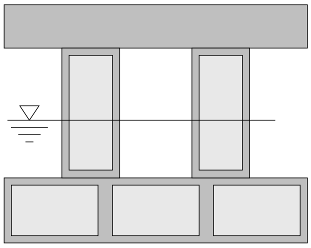
### *Pontoon Type*

A floating structure is generally made into the form of pontoon. Pontoon has the shape of a box as shown in the Fig. 2 (a). In the case of constructing large size floating structure, a target structure is composed with many pontoons connected with each other by welding or beam-connecting. This type has been widely applied with many advantages such as maximized submerged volume for securing buoyancy, practical use of inner space for storage or machinery room, simple details and so on [5, 6, 7].

However, this system is unable to absorb wave impact energy because the sides face up to the wave action. The wave-induced impact energy is delivered entirely to the structure and it increases motion and bending moment of pontoon. Consequently, this system is vulnerable to wave-induced bending moment and hydrodynamic motion so in order to satisfy design criteria for strength of floating structures, it should be required to have a large cross section and depth. These disadvantages limit the application of floating structures of this type to only nearly-still water conditions and constrain the multi-purpose application of floating structures to wild offshore conditions [3, 7].



(a) PONTOON TYPE



(b) SEMI-SUBMERSIBLE TYPE

FIG. 2 TYPES OF FLOATING STRUCTURES

### *Semi-submersible Type*

For this type, pontoon for buoyancy is located at the bottom of a structure and submerged entirely. Some columns are placed on the pontoon and support deck which is working area. Deck is entirely above the water surface as shown in the Fig. 2 (b). Waves flow through the columns so the semi-submersible is less affected by the waves than a pontoon type. Therefore this type is of advantage in wild sea and generally used for oil drilling rig located at deep sea.

However this type has relative disadvantages over the pontoon type that it requires its own pontoon for buoyancy while entire structure contributes to the buoyancy in pontoon type. Furthermore there should be much more complex considerations such as squeeze/pry loads those make the columns move within and without repeatedly for successive waves [8].

## Experimental Program

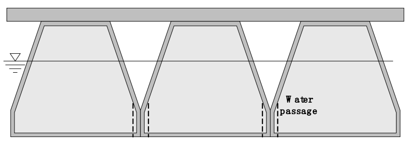
### *Special Pontoon Shape*

In this study, a different shape of pontoon with increased resistance for hydrodynamic motion was tested to create more stable marine space. It has a prismoidal shape instead of box shape as shown in Fig. 3. The primary difference from conventional box type is the front face hitting wave. The front face of box type pontoon is a shape of rectangular whereas that of prismoid type is trapezoid. If these two section types have same bottom width, the latter has an empty space due to its contracted width of top. Wave can flow through this empty space while rectangular section interrupts flow of wave. This affects the impact energy to the face and consequently hydrodynamic motion of pontoon. The secondary feature is that there could be a seawater passage at the point where four corners of pontoons meet each other.

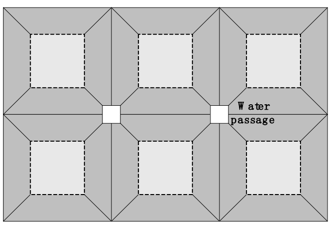
Significant features of this type in short again are as follows:

- Waves flow through the space between lateral sides of pontoons.
- Water passage located at the corners of pontoons plays a role as a damper for heaving motion because it is a form of funnel.

These are for keeping the structure more stable with taking advantages of both pontoon and semi-submersible types.




(a) PROFILE




(b) PLAN

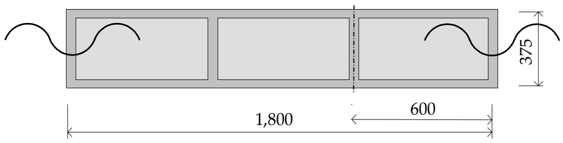
FIG. 3 LAYOUT OF PRISMOIDAL SHAPE PONTOON

### *Specimens*

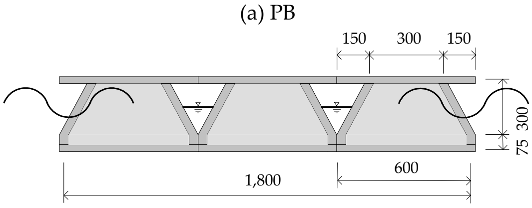
A series of small-scale tests with various wave cases were performed on pontoon models with different shapes. A total of four small-scale pontoon models with different lateral shapes and bottom details were fabricated, as shown in Fig. 4. The dimensions of the small-scale pontoon models were 1,800(L) × 600(W) × 375(H) mm with a scale factor of 1:25, which simulates a floating pier.

In order to consider the effects of the lateral shape on wave-induced hydraulic pressure on the bottom and acceleration of pontoon models, two pontoons with different lateral shapes were selected; box type and prismoid type. The prismoid type pontoon was introduced to reduce the large wave-induced bending moment of the box type pontoon. The prismoid type pontoon has composed of a semi-opened side section to penetrate the wave impact energy. The corresponding pontoon models to lateral shapes of box and prismoid type were denoted as PB and PP, respectively. Also, in order to consider the effects of the bottom shape on wave-induced hydraulic pressure and acceleration, two different bottom shapes were selected; planar and waffled. The waffled bottom plate was introduced to increase contact area with the water and to add horizontal water pressure as well as vertical water pressure at the bottom plate. The corresponding pontoon models to bottom shapes of plane and waffled type were denoted as -P and -W, respectively.

The pontoon models were made of steel plate with a thickness of 4.5 mm. In order to idealize the waffled bottom shape, 50 mm wide steel strip were attached to the bottom surface at 150 mm intervals. All of the steel to steel joints were fully welded to prevent flooding.




(a) PB




(b) PP

FIG. 4 SMALL-SCALE PONTOON MODELS

(a) PB-W

(b) PP-W

FIG. 5 WAFFLED SURFACE OF PONTOON

### *Wave Loads and Gauges*

The small-scale pontoon models were tested under the five different wave conditions presented in Table I. The wave variables for the small-scale test were wave height and wave period [9]. For the full-scale model, three cases of wave height ($H_W$) 1.8 m, 2.8 m, and 3.6 m were selected and these were scale downed to 0.07 m, 0.11 m, and 0.14 m for the small-scale model. Also, three cases of wave period ($P_W$) 3.8 sec., 5.4 sec., and 7.6 sec. were selected and these were scale downed to 0.76 sec., 1.07 sec., and 1.63 sec. for the small-scale model. These three cases of wave periods were corresponded to the wave length ($L_W$) of 0.91 m ($L_W$ = 0.5L), 1.77 m ($L_W$ = 1.0L), and 3.58 m ($L_W$ = 2.0L), respectively, as presented in Fig. 6, where L is the pontoon length.

Six hydraulic pressure gauges were attached to the bottom surface of the pontoon models and three accelerometers were installed on the top surface, as shown in Fig. 7. In order to measure hydraulic pressure and motion precisely, water pressure gauges with a measurement range of 0.005 kN/cm$^2$ and accelerometers with 0.5 g were used. The wave-induced hydraulic pressure and acceleration by motion were measured during the tests.

TABLE I WAVE CASES

| No. | $H_W$(m) | $P_W$(sec) | $L_W$(m) | $L_W$ / L |
|---|---|---|---|---|
| 1 | 0.07 (1.8) | 1.07 (5.4) | 1.8 (45.0) | $L_W$ = 1.0L |
| 2 | 0.11 (2.8) | 1.07 (5.4) | 1.8 (45.0) | $L_W$ = 1.0L |
| 3 | 0.14 (3.6) | 1.07 (5.4) | 1.8 (45.0) | $L_W$ = 1.0L |
| 4 | 0.11 (2.8) | 0.76 (3.8) | 0.9 (22.5) | $L_W$ = 0.5L |
| 5 | 0.11 (2.8) | 1.63 (7.6) | 3.6 (90.0) | $L_W$ = 2.0L |

* Outside ( ): small-scale, inside ( ): full-scale

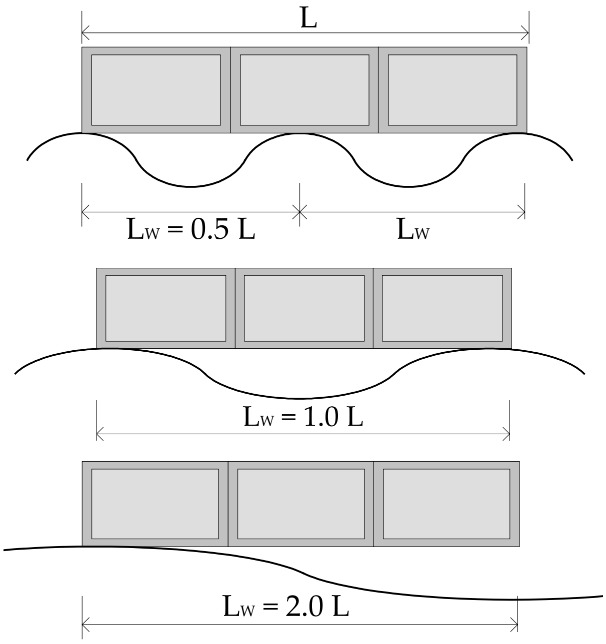



FIG. 6 WAVE LENGTH RATIOS TO PONTOON LENGTH

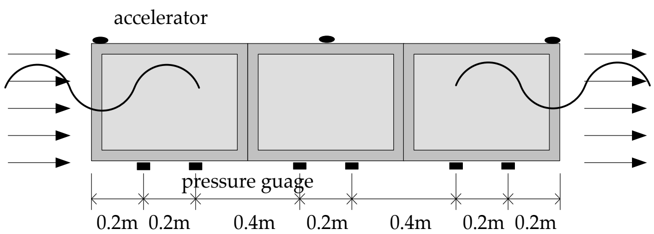
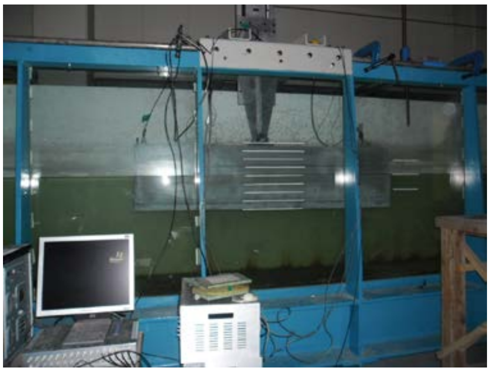



FIG. 7 INSTALLATION OF GAUGES

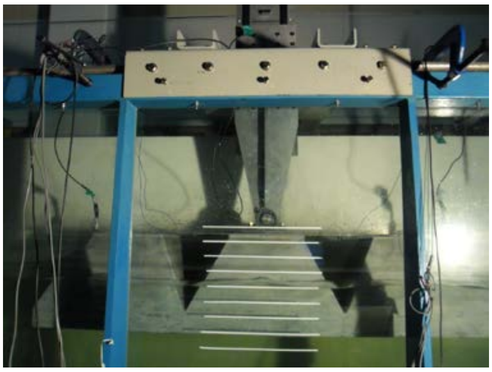
### *Test Set-up*

In order to investigate wave-induced hydraulic pressure and acceleration by motion, experimental studies were conducted to the floating structures of pontoon type, as shown in Fig. 8. Small-scale tests were conducted using the flume of the Korea Institute of Construction Technology. The dimensions of the flume are 50(L) × 1.2(W) × 1.5(H) m and the small-scale pontoon models were placed in the longitudinal direction of the flume.

A mechanical frame was specially designed and fabricated to allow only heaving and pitching motion of pontoons with the minimum friction and to restrain other hydrodynamic motions of sway, surge, rolling, and yawing [10]. A vertical pole was connected to the vertical frame with many ball bearings to allow a vertical heaving motion and the vertical pole was connected to the pontoon models with a hinge bearing to allow a rotational pitching motion with minimum friction.



(a) Box type specimen (PB-P)



(b) PRISMOID TYPE SPECIMEN (PP-P)

FIG. 8 TEST SET-UP

## Test Results

### *Wave-Induced Hydraulic Pressure by Wave Condition*

The wave-induced hydraulic pressures measured at the middle part of pontoon bottom are presented at Table II, Fig. 9 and Fig. 10. The measured hydraulic pressures had different tendencies in terms of wave height and wave period.

The wave number 1, 2, and 3 had same period and wave length while the wave height of wave number 2 and 3 were 1.5 and 2.0 times bigger than wave number 1, respectively. The wave-induced hydraulic pressures at the bottom were directly dependent on the wave height. Irrelatively pontoon shape, as the wave height increased, the wave-induced hydraulic pressures also increased linearly, as presented in Fig. 9 and Fig. 10. However, the pressures of prismoid type (PP-P) were smaller than those of box type (PB-P) in most cases and the difference between maximum and minimum of pressure of prismoid type was about 76% of box type.

In the case of wave period, although the wave-induced hydraulic pressure increased linearly until the median wave period of 1.07 sec (wave number 4, 2, and 5), no longer hydraulic pressures increased linearly to the wave period at the long wave period of 1.63 sec, as presented in Fig. 9 (d), (b), and (e) and Table II. In the case of the short wave period of 0.76 sec, the wave-induced hydraulic pressure presented a large variance. At all cases, the periods of measured hydraulic pressures coincided with the wave periods.

TABLE II MEASURED MAX. AND MIN. PRESSURE

| Wave no. | PB-P | | | PP-P | | | Decrease rate |
|---|---|---|---|---|---|---|---|
| | Max. | Min. | Max. -Min. | Max. | Min. | Max. - Min. | |
| 1 | 6.9 | -8.8 | 15.7 | 4.9 | -5.9 | 10.8 | 31.2% |
| 2 | 11.8 | -13.7 | 25.5 | 9.8 | -6.9 | 16.7 | 34.6% |
| 3 | 16.7 | -15.7 | 32.3 | 21.6 | -8.8 | 30.4 | 6.0% |
| 4 | 5.9 | -7.8 | 13.7 | 5.9 | -5.9 | 11.8 | 14.2% |
| 5 | 7.8 | -10.8 | 18.6 | 21.6 | -12.7 | 34.3 | -84.3% |

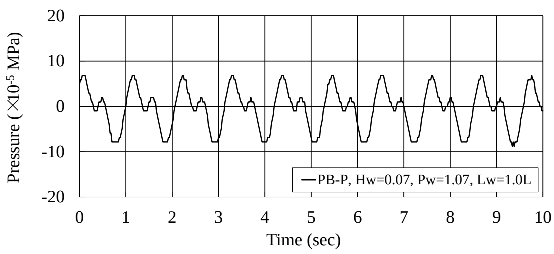
### *Wave-Induced Hydraulic Acceleration by Wave Condition*

#### *1) Acceleration by Wave Height*

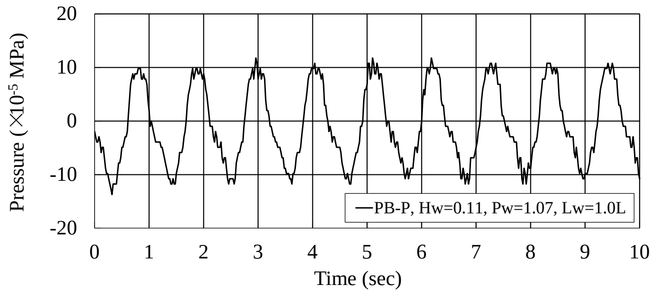
Fig. 11 and Fig. 12 and Table III and IV show the measured acceleration at the centre and the stern for the parameters in Table I. Graphs were plotted only for ten seconds after a few waves passed.

The wave number 1, 2, and 3 had same period and wave length while the wave height of wave number 2 and 3 were 1.5 and 2.0 times bigger than wave number 1, respectively.

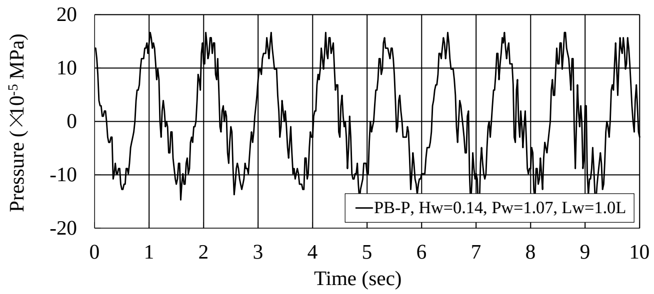
It was observed from of Fig. 11 (a), (b), and (c) that the higher wave height, the more heavily both specimens shook like the results of wave length. However the extent of shaking of PP-P type was smaller than that of PB-B. The band widths (difference between maximum and minimum accelerations) at the centre for prismoid pontoon were about 70%, 30%, and 30% of those of box type for the cases that wave heights were 0.07 m, 0.11 m, and 0.14 m as shown in Table III. The PP-P showed decreased acceleration of 29~68% over PB-P.



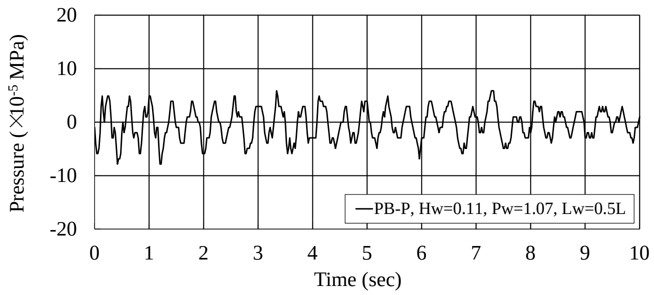

(a) WAVE 1



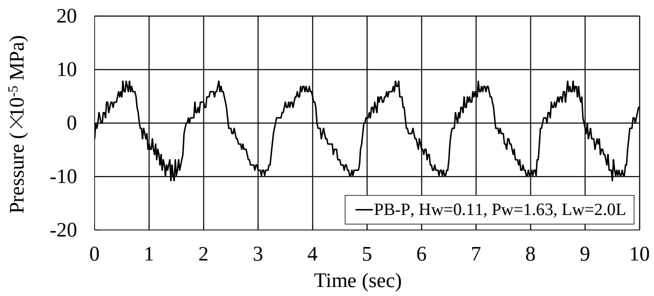

(b) WAVE 2




(c) WAVE 3

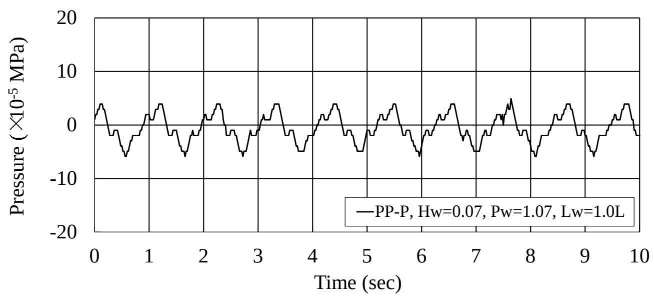



(d) WAVE 4

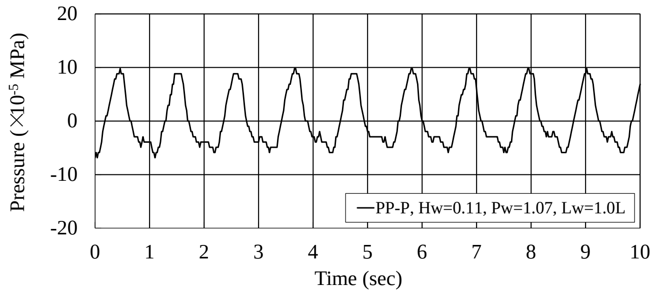



(e) WAVE 5

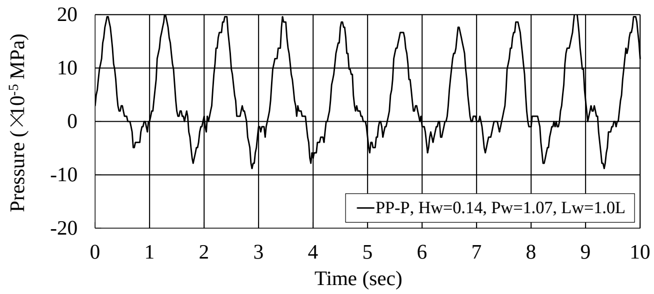
FIG. 9 MEASURED PRESSURES FOR BOX TYPE PONTOON (PB-P)



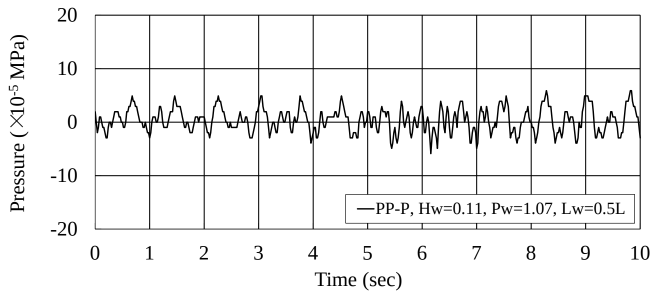

(a) WAVE 1



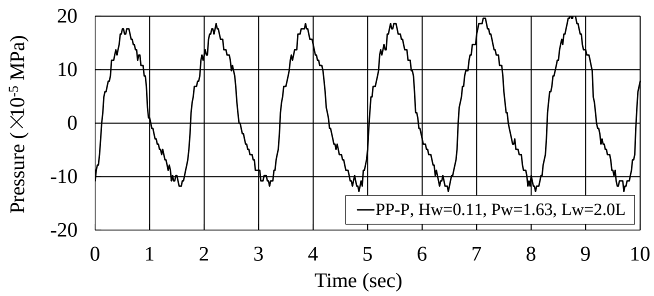

(b) WAVE 2




(c) WAVE 3

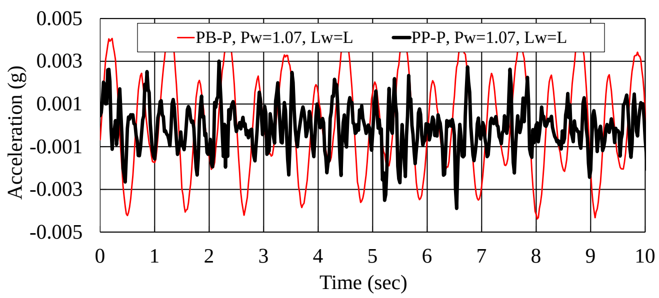



(d) WAVE 4

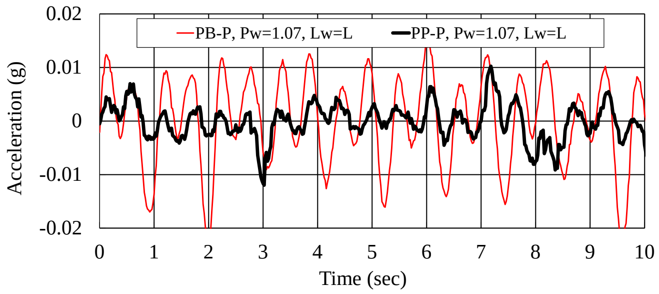



(e) WAVE 5

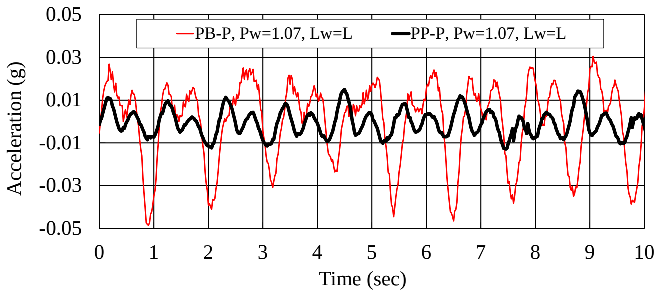
FIG. 10 MEASURED PRESSURES FOR PRISMOID TYPE PONTOON (PP-P)



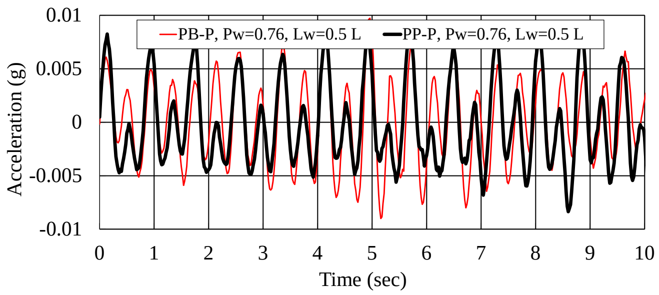

(a) WAVE 1



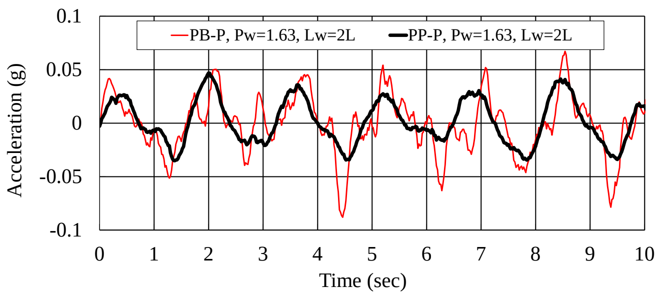

(b) WAVE 2




(c) WAVE 3

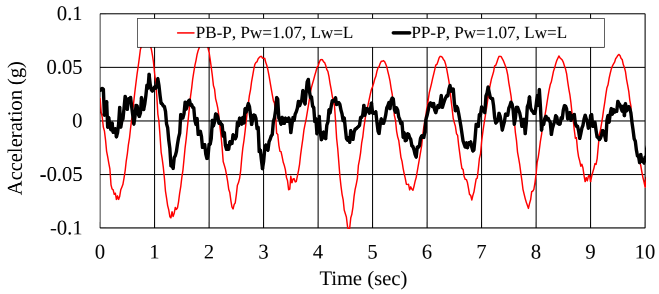



(d) WAVE 4

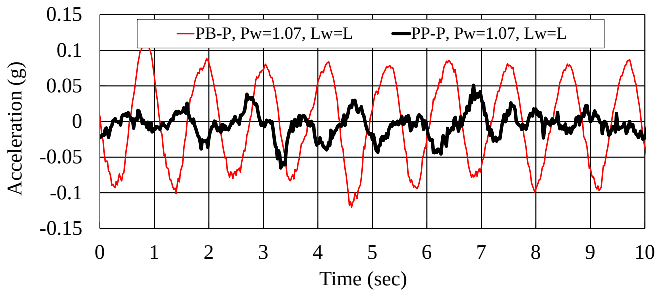



(e) WAVE 5

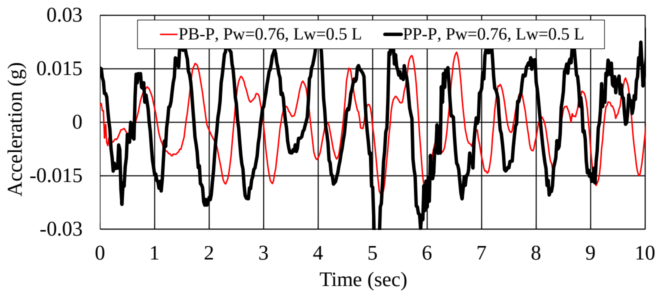
FIG. 11 ACCELERATION AT CENTER



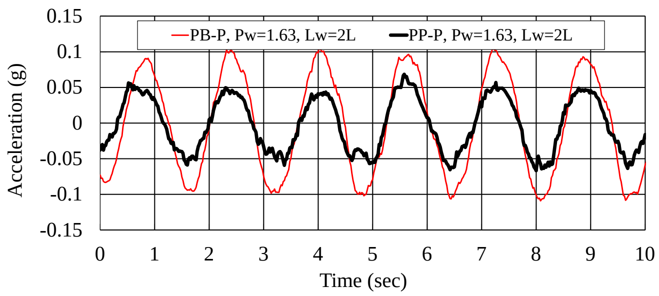

(b) WAVE 2




(c) WAVE 3

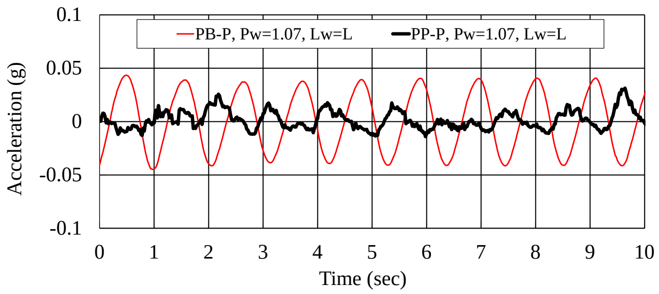



(d) WAVE 4




(e) WAVE 5

FIG. 12 ACCELERATION AT STERN




(a) WAVE 1

TABLE III VARIATION OF ACCELERATION AT CENTER BY WAVE HEIGHT

| Hw (m) | PB-P | | PP-P | | |
|---|---|---|---|---|---|
| | Avg. band width (g) | Increase rate (vs. 0.07) | Avg. band width (g) | Increase rate (vs. 0.07) | Decrease rate (vs. box type) |
| 0.07 | 0.0074 | - | 0.0053 | - | 29% |
| 0.11 | 0.0256 | 347% | 0.0083 | 157% | 68% |
| 0.14 | 0.0623 | 844% | 0.0204 | 387% | 67% |

TABLE IV VARIATION OF ACCELERATION AT STERN BY WAVE HEIGHT

| Hw (m) | PB-P | | PP-P | | |
|---|---|---|---|---|---|
| | Avg. band width (g) | Increase rate (vs. 0.07) | Avg. band width (g) | Increase rate (vs. 0.07) | Decrease rate (vs. box type) |
| 0.07 | 0.0810 | - | 0.0283 | - | 65% |
| 0.11 | 0.1402 | 173% | 0.0491 | 173% | 65% |
| 0.14 | 0.1795 | 222% | 0.0571 | 202% | 68% |

This phenomenon also was observed at the stern as shown in Fig. 12 (a), (b), and (c), and Table IV. Decrease rate of acceleration of PP-P (prismoid type) over PB-P (box type) was almost constant as the height increased. On the average with the results in Table III and IV, prisomodal type showed about 60% decreased hydrodynamic motion. It could be noted that the increase rates of 0.11 m and 0.14 m over 0.07 m for box type were 347% and 844% at the centre, however 173% and 222% at the stern. Acceleration inherently means displacement because acceleration is the rate of change of velocity with time and velocity is the rate of change of displacement with time. Therefore, the acceleration at the stern and the centre mean the extent of rotation and heaving, respectively.

The increase rates of box and prismoid type at the stern were almost same but the increase ratio of box type at the centre was bigger than that of prismoid type. This could mean that box type moved up and down heavily more than prismoid type. Consequently, prismoid type showed more stable motion than box type.

### 2) *Acceleration by Wave Length*

In the case of wave length, the wave lengths of wave number 4, 2, and 5 in Table I were the 0.5, 1.0, and 2.0 times of the length of specimen and had same wave height.

When the wave length is shorter than that of specimen, it does not affect so much to the motion of specimen while longer, structure shakes heavily. However, the accelerations of both shapes were increased according to the increase of wave length, especially when the wave length is two times of specimen length.

When the wave length is 0.5 times of that of specimen (Fig. 11 (d)), the band width of acceleration at the centre in Table IV were almost same in box and prismoid pontoons. For the case that the wave length was same with that of specimen, the acceleration of PB-P increased over 200% while about 70% for PP-P (Fig. 11 (b)), and 900% and 500%, respectively when the wave length is 2 times of that of specimen (Fig. 11 (e)).

TABLE V VARIATION OF ACCELERATION AT CENTER BY WAVE LENGTH

| Lw | PB-P | | PP-P | | |
|---|---|---|---|---|---|
| | Avg. band width (g) | Increase rate (vs. 0.5L) | Avg. band width (g) | Increase rate (vs. 0.5L) | Decrease rate (vs. box type) |
| 0.5L | 0.0122 | - | 0.0116 | - | 5% |
| L | 0.0256 | 211% | 0.0083 | 72% | 68% |
| 2L | 0.1129 | 929% | 0.0641 | 554% | 43% |

TABLE VI VARIATION OF ACCELERATION AT STERN BY WAVE LENGTH

| Lw | PB-P | | PP-P | | |
|---|---|---|---|---|---|
| | Avg. band width (g) | Increase rate (vs. 0.5L) | Avg. band width (g) | Increase rate (vs. 0.5L) | Decrease rate (vs. box type) |
| 0.5L | 0.0290 | - | 0.0398 | - | -37% |
| L | 0.1402 | 1153% | 0.0491 | 123% | 65% |
| 2L | 0.1979 | 1628% | 0.1137 | 286% | 43% |

The prismoid type decreased acceleration of 5~68%. This phenomenon also was observed at the stern as shown in Fig. 12 (b), (d), and (e), and Table VI. It is noted that the increase rates by wave length is bigger than by wave height, significantly for acceleration at the stern. This means that pontoon could be affected more sensitively by wave length.

Fig. 13 shows a graph plotted acceleration for wave length divided with wave height. The accelerations showed a tendency that the acceleration increased or decreased in a specific range of the ratio of wave length divided by wave height.

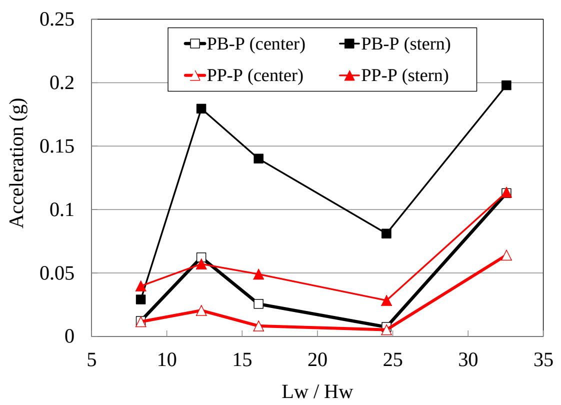
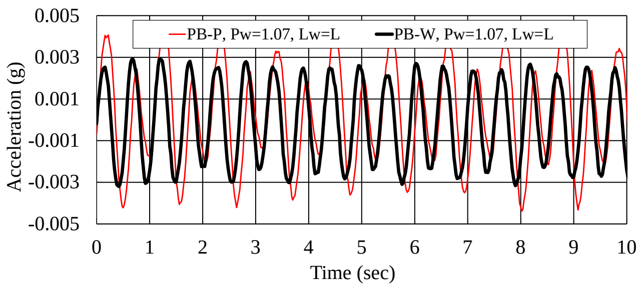
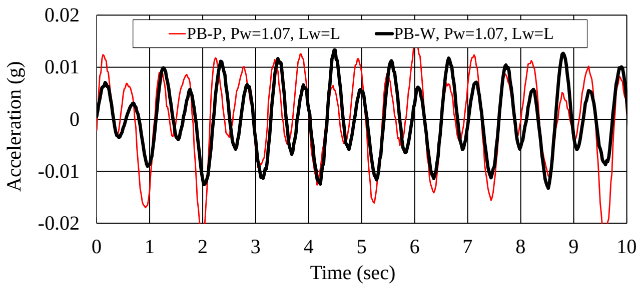



FIG. 13 EFFECT OF HEIGHT AND LENGTH OF WAVE

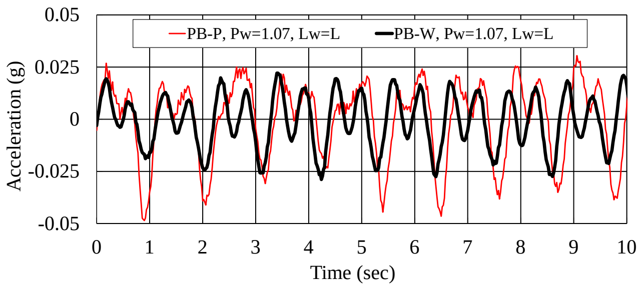
The accelerations of box type were bigger than those of prismoid type irrelatively with the ratio and position and so were the differences between accelerations measured at the centre and the stern. Even though the acceleration of the centre of box type is same with that of prismoid type, the fact that the acceleration at the stern of box type was bigger than that of prismoid type means box type rotated heavily more than prisomoid type. Consequently, the airgap and the prismoid shape showed good effect decreasing hydrodynamic motion.



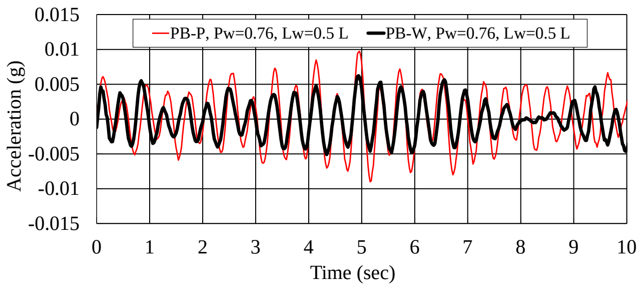

(a) WAVE 1



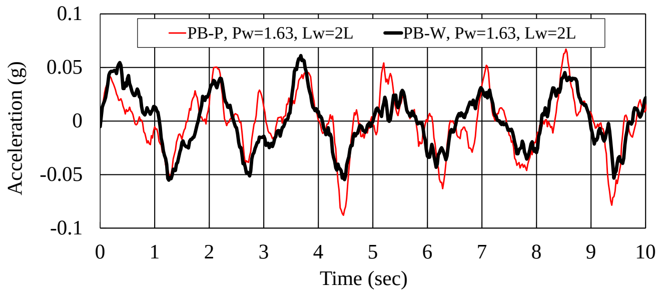

(b) WAVE 2




(c) WAVE 3

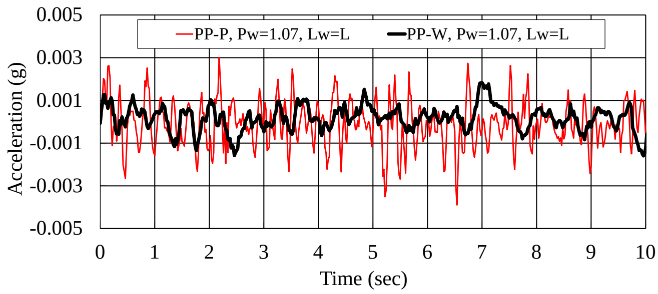



(d) WAVE 4

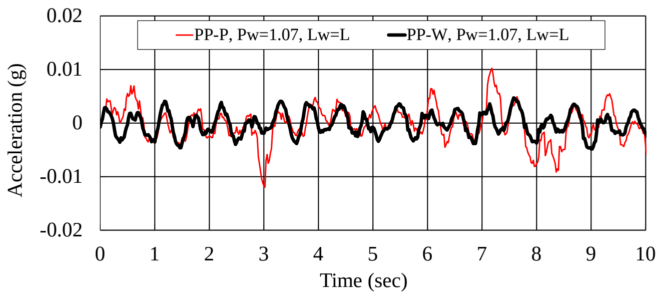



(e) WAVE 5

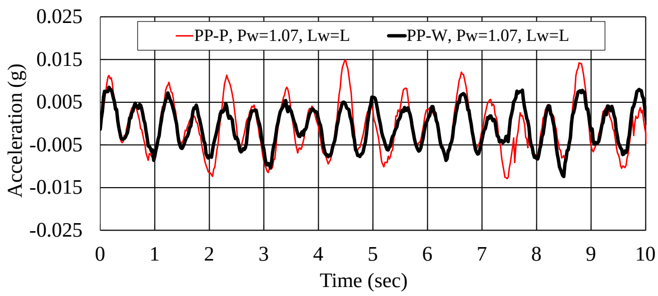
FIG. 14 ACCELERATION DIFFERENCE BETWEEN PLANAR AND WAFFLED SURFACE FOR BOX TYPE PONTOON



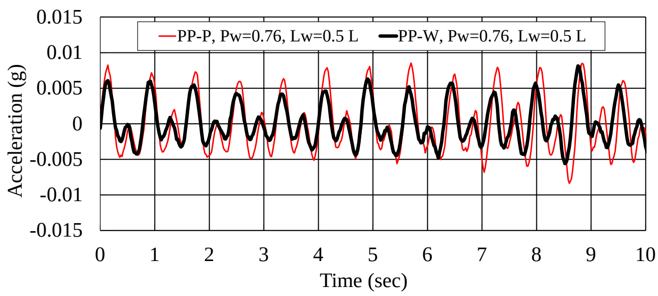

(a) WAVE 1



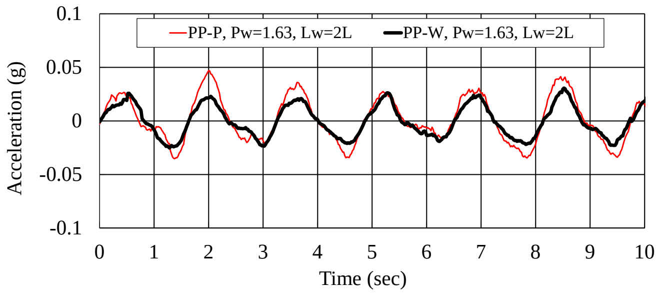

(b) WAVE 2




(c) WAVE 3




(d) WAVE 4




(e) WAVE 5

FIG. 15 ACCELERATION DIFFERENCE BETWEEN PLANAR AND WAFFLED SURFACE FOR PRISMOID TYPE PONTOON

### 3) *Effect of Bottom Surface Shape*

Fig. 14 and Fig. 15 show measured accelerations of pontoons with planar and waffled surfaces for box and prismoid type, respectively.

It was expected that the decreased hydraulic pressure due to disturbed wave by waffled shape could make pontoon stabilized. Even though there was a little difference of accelerations between planar and waffled surfaces for both pontoon types, it is careful that it is from the play of waffled surface.

This needs further study whether it is due to the relative size of waffled part.

## Conclusions

In this study, in order to investigate the wave-induced buoyancy effects, experimental studies were conducted on pontoon-type floating structures. A series of small-scale tests with various wave cases were performed on the pontoon models. A total of four small-scale pontoon models with different lateral shapes and bottom details were fabricated and tested under the five different wave cases. Six hydraulic pressure gauges and three accelerometers were attached to the bottom and top surfaces of the pontoon models and the wave-induced hydraulic pressure and acceleration were measured during the tests. Finally, hydraulic pressures subjected to the bottoms of the pontoon models and the changes of acceleration were compared with each other.

As the results of this study, it was found that the wave-induced hydraulic pressures at the bottom were dependent on the wave period as well as the wave height. The hydraulic pressures linearly increased according to the wave height and period. However, in the case of long wave periods, the wave-induced hydraulic pressure no longer increased. Also, it was found that whereas the waffled bottom shape hardly influenced the wave-induced hydraulic pressure, the prismoidal lateral shape significantly influenced the wave-induced hydraulic pressure subjected on the bottoms of floating structures.

The prismoidal lateral shape showed more stable motion than box type regardless of wave length and height, especially for severe case when the wave length or height become big. On average, the amplitude differences of acceleration were decreased about 55% as the wave height changed up to two times and 40% as the wave length changed from 0.5L to 2L.

Consequently, the air gap effects of the prismoidal shape contribute to decreasing the wave-induced hydraulic pressure and acceleration due to absorption of wave impact energy.

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